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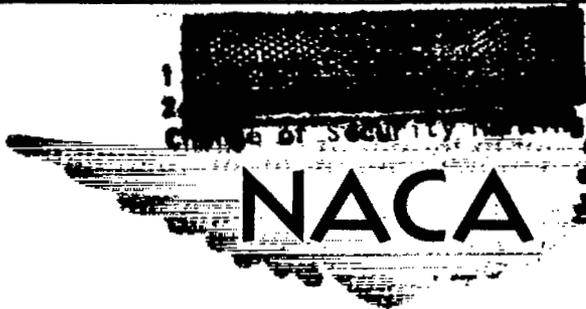
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RESEARCH MEMORANDUM

EFFECT OF DISSOCIATION ON EXHAUST -NOZZLE PERFORMANCE

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CLASSIFIED DOCUMENT

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

EFFECT OF DISSOCIATION ON EXHAUST-NOZZLE PERFORMANCE

By T. W. Reynolds

SUMMARY

Net jet thrusts for stoichiometric hydrocarbon-air, hydrogen-air and pentaborane-air mixtures are compared for equilibrium and frozen expansion in the exhaust nozzle at flight Mach numbers up to 10. Net jet thrusts for equilibrium flow were three to five times that for frozen flow at Mach 10 for the three fuels cited, a hydrocarbon $(CH_2)_n$, hydrogen, and pentaborane.

Examinations of the dissociation products involved and the energies associated with them, for the hydrocarbon- and hydrogen-air mixtures indicated that: a major portion of the dissociation energy for the hydrocarbon mixture is involved in the carbon monoxide molecule. Recent rate data indicate that this molecule would not be in equilibrium during the expansion process. These examinations also indicated that in the hydrogen-air mixtures, the dissociation energy is distributed in H_2 , OH, H, and O. Recombinations of the H and O atoms and the OH radical probably follow equilibrium. It is uncertain whether H_2 reactions will follow an equilibrium or frozen path. Reactions involving NO decomposition will probably follow frozen flow. Fortunately, the amount of energy involved in the NO molecule is small for the cases examined.

INTRODUCTION

The continued extension of flight velocity to higher Mach numbers has brought into focus certain considerations that were unimportant at low flight velocities. One such problem is the effect of dissociation and recombination reactions on exhaust-nozzle thrust, which is reported herein.

In an air-breathing engine, as the flight Mach number increases the ram-air temperature increases (fig. 1). When fuel is added to the air in the combustor to raise the temperature level so that expansion through the exhaust nozzle will provide thrust, the temperature rise of the combustion products is limited by the increasing amounts of energy

that are used in the dissociation reactions (fig. 1). The equilibrium temperature of the exhaust products increases as the Mach number increases, but the temperature rise becomes smaller. In fact, near Mach 10, no temperature rise at all will occur with the hydrocarbon fuel used.

If no dissociation occurred, the temperature level would be that shown by the top curve of figure 1 for complete oxidation. The extent of the temperature deviation for the combustion products with and without dissociation is an indication of the magnitude of the energy involved in dissociated products.

In engine performance analysis, it is customary to assume that the exhaust gas entering the exhaust nozzle is in the equilibrium state. When this gas expands through the nozzle, the amount of thrust attainable will depend upon the extent of recombination reactions, which yield chemical energy to be converted into kinetic energy of the exhaust stream. The extent to which recombination occurs depends upon the reactions involved, their respective reaction rates, and the residence time in the nozzle.

Modes of energy storage other than dissociation may be involved, such as rotational and vibrational energies, which may have relaxation times long enough to affect the flow variables. A discussion of these energy modes is found in references 1 to 4. In this report, equilibrium is assumed with respect to these modes.

Herein are discussed: (a) the magnitude of the thrust differences between chemically frozen and chemical equilibrium flow during the exhaust-nozzle expansion process, (b) the types of chemical species in which the major fractions of dissociation energy are involved, and (c) reaction rate information required to establish the approach to equilibrium flow.

The fuels considered are a hydrocarbon $(CH_2)_n$, hydrogen H_2 , and pentaborane B_5H_9 .

SYMBOLS

- A area, sq ft
 F_n net jet thrust, lb
f fuel-air weight ratio
g acceleration due to gravity, 32.2 ft/sec²

ΔH enthalpy difference, Btu/lb of mixture
 J mechanical equivalent of heat, 778 ft-lb/Btu
 M inert body
 p static pressure, lb/sq ft
 t static temperature, $^{\circ}R$
 V velocity, ft/sec
 w_a weight flow of air, lb/sec
 γ ratio of specific heats

Subscripts:

a air
 c combustor
 eff effective
 i inlet
 j jet exhaust
 n net
 O free stream

EXPANSION CALCULATIONS

The net jet thrust for a ramjet engine is

$$F_n = (p_A + \frac{w_a}{g} V)_j - (p_A + \frac{w_a}{g} V)_i - p_O(A_j - A_O) \quad (1)$$

For complete expansion of the exhaust, equation (1) reduces to

$$\frac{F_n}{w_a} = (1 + f) \frac{V_j}{g} - \frac{V_O}{g} \quad (2)$$

The jet velocity is calculated from the energy relation

$$V_j = \sqrt{2gJ \Delta H} \quad (3)$$

which involves the enthalpy change occurring in the expansion process.

The comparison of thrust for a chemical equilibrium and a chemically frozen expansion process, then, is made by obtaining the enthalpy change for an isentropic expansion under each condition.

In making engine performance calculations, it is generally assumed that the gas mixture entering the exhaust nozzle is an equilibrium mixture of combustion products.

Calculated equilibrium compositions for combustion products of several fuel-oxidant combinations at various temperature and pressure levels are available in references 5 to 7. In addition, thermodynamic charts and tables for combustion products of air and fuels containing boron, carbon, hydrogen, and oxygen are also available (refs. 8 to 10). For example, table I gives the composition data for a stoichiometric mixture of a hydrocarbon fuel with air. The composition data at 3.4 atmospheres and 5430° R, might correspond to the exhaust-nozzle inlet conditions for a ramjet engine at Mach 7 at an altitude of 100,000 feet. If this mixture of a hydrocarbon and air expanded through the nozzle maintaining this composition (frozen flow), the enthalpy change would be the summation of the sensible heat content changes for each constituent.

If the mixture expanded while maintaining equilibrium composition at each temperature and pressure throughout (equilibrium flow), the compositions at pressure levels of 1 and 0.1 atmosphere would be those also shown in table I. During this expansion, considerable reaction would have occurred and the products would approach those of a complete reaction without dissociation. In the equilibrium expansion process, then, there is enthalpy change from heats of reaction in addition to the enthalpy change due to the sensible heat capacity of the products. There may also be a change in the molecular weight of the products. Some typical reactions possible in a hydrocarbon-air system along with the heats involved are shown in table II. This list is not intended to be complete, but it is included to illustrate the types of reaction involved. It may also serve to suggest the complexity of an attempt at a complete and rigorous treatment of the expansion process based on the reaction rates of all possible reactions. (This subject is discussed in the section Reaction Rates.)

Net jet thrusts per pound of airflow were calculated from equation (2) for three fuels: a typical hydrocarbon, hydrogen, and a typical boron fuel, pentaborane. Calculations were made for a range of Mach numbers up to 10 at an assumed altitude of 100,000 feet and for a stoichiometric mixture in each case.

Combustor pressures were obtained assuming a kinetic energy efficiency for the diffuser of 0.875. The combustor pressures obtained in this manner are shown in figure 2.

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Enthalpy changes for equilibrium expansions were calculated from the thermodynamic charts of reference 8. Enthalpy changes for frozen expansion processes were calculated by using the tabulated heat-capacity data in reference 8. The assumption was made that, at the same temperature, the sensible heat capacity of a dissociated mixture was the same as that of a completely reacted mixture without dissociation. The net jet thrusts per pound of air so calculated are shown in figure 3. For all fuels, the thrust for a chemically frozen expansion is lower than for an equilibrium expansion and decreases more rapidly as the Mach number is increased. The difference in net jet thrusts, therefore, increases as Mach number is increased. At Mach 10, for example, the net jet thrusts for frozen flow are only one-third to one-fifth of those for equilibrium flow for the fuels used (a typical hydrocarbon, hydrogen, and pentaborane). It can readily be surmised that the thrust margin between the equilibrium and frozen expansion process may be the difference between an operative and a nonoperative system at high flight Mach numbers. In any case, a considerable difference in fuel economy is indicated between the two extremes of equilibrium and frozen flow.

The thrust difference between the two expansion processes is, of course, dependent upon the amount of dissociation, which, in turn, depends upon the temperature and the pressure level. The thrust comparison, then, is dependent upon the altitude and upon the assumed pressure recovery for the engine inlet. The curves of figure 3 were plotted for a diffuser kinetic energy efficiency of 0.875. Net jet thrusts were also calculated for the hydrogen-air mixture for a kinetic energy efficiency of 0.95. The pressure levels for this efficiency are shown in figure 2. The net thrusts for hydrogen are plotted in figure 4 in which it can be seen that although the differences in net thrust are about the same at either efficiency level, the ratio of equilibrium to frozen thrust is considerably different.

These thrust calculations are for complete expansion to the ambient pressure in each case. The principal factor in the higher thrusts for the higher diffuser efficiency case (0.95), then, is the higher pressure ratio available for the expansion. This is mentioned here only to emphasize the sensitivity of a comparison, such as the ratio of net jet thrusts to the assumed pressure recoveries and altitudes.

It is interesting to note, however, that an improvement in diffuser pressure recovery of the magnitude shown (fig. 4) would yield nearly the same thrust for a completely frozen expansion as is obtained for a complete equilibrium expansion at the lower diffuser efficiency level. For the same airflow, also, the higher diffuser efficiency case would yield a much smaller diameter nozzle.

The completely frozen or complete equilibrium expansion processes essentially represent the extremes of the possible process to be expected. If all the chemical reaction rates involved were very fast

compared with the residence time of the gas in the nozzle, equilibrium flow would be expected. If all the reaction rates were very slow compared with this residence time, completely frozen composition expansion would be expected. The estimation of the approach of the expansion process to equilibrium or frozen flow, therefore, relies on information regarding the reactions involved, their respective reaction rates, and the residence time in the nozzle. Some discussions on this subject relative to rocket-engine nozzles may be found in references 11 to 16.

RESULTS AND DISCUSSION

Dissociation Energies

The importance of the reaction rates of the many possible steps might be emphasized by examining the amount of dissociation energy involved in each of the various chemical products. Then, the more important reactions to consider will be those involving constituents that hold a large part of the dissociation energy.

Equilibrium composition data are shown in table III(a) for a stoichiometric hydrocarbon-air mixture at 5430° F and 3.4 atmospheres. These compositions correspond to those that might exist in the ramjet combustor at Mach 7 at an altitude of 100,000 feet. Tables III(b) and (c) contain similar data for a stoichiometric hydrogen-air mixture, and a stoichiometric pentaborane-air mixture, respectively. If the constituents all react to the complete oxidation products CO_2 , H_2O , and N_2 , the amount of heat evolved (shown in table III) is the energy involved in dissociated products. If the reactions are assumed to proceed according to the reaction paths indicated in the table, a certain percentage of the total dissociation energy can be associated with each chemical constituent. For example, in table III(a), approximately 59 percent of the total energy in dissociated products is involved in the CO, and 17 percent in the OH species for a typical hydrocarbon fuel.

For the hydrogen fuel (table III(b)) at 5.2 atmospheres and 5710° F, approximately 27 to 30 percent of the dissociation energy is involved in each of the products H_2 , OH, and H, while about 9 percent is involved in the atomic oxygen O. For the pentaborane fuel, approximately 66 percent of the dissociation energy is in the BO molecule and about $11\frac{1}{2}$ percent in the OH radical. The division of energy in this manner is, of course, somewhat arbitrary in that it depends upon the particular reactions that are selected to obtain complete oxidation products. The reasons for the particular reaction scheme chosen are discussed in the section Reaction Rates.

The energy in dissociated products, as shown in table III, represents the major portion of the difference in the enthalpy change between the equilibrium and frozen expansion process, provided that the expansion is carried to a low enough temperature. The expansion calculations made herein are all for conditions where the equilibrium exhaust products would be nearly complete oxidation products. In the calculations involving pentaborane-air combustion products, the B_2O_3 was assumed to remain in the gaseous phase.

Reaction Rate

Consideration of the data of table III indicates what reactions, or rather what chemical products are important with respect to reaction-rate information.

For the hydrocarbon fuel, a large fraction of the dissociation energy is involved in the CO molecule, and a lesser amount in the OH radical. Reaction rates involving CO and OH will obviously be of major importance in establishing the approach to equilibrium flow for the hydrocarbon fuel. For the hydrogen fuel, reactions involving H_2 , OH, H, and O will all be of major importance.

For both the hydrocarbon and hydrogen fuel, the fraction of energy involved in the NO molecule is so small that the rate of reaction involving this constituent is probably of minor importance. This is fortunate, since such reactions are known to be rather slow compared with exhaust-nozzle residence times (refs. 14 and 17 and ref. 18, p. 852).

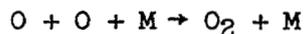
If the complete system of reaction equations involved in the expansion process were known, and, further, if the reaction rates of these equations were known, the approach of the flow to the equilibrium or frozen process might be established. A procedure for estimating whether the flow is near equilibrium or near frozen is outlined in reference 17 along with some illustrative examples. One reaction is examined at a time at some point in the nozzle where the temperature, concentration, and other parameters of the flow are known.

Analytical expressions indicative of near-equilibrium or near-frozen flow are derived in reference 17. The parameters involved are the reaction-rate constants, concentrations, equilibrium constants, and residence times. Analyses such as these have been made for several reaction systems for which the reaction-rate constants are known or can be estimated, such as hydrogen atom recombinations, nitric oxide decomposition, and hydrogen-fluorine reactions.

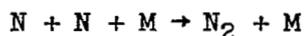
At the conditions of temperature, concentrations, and residence times for comparatively small scale rocket engines (where the temperature change rates are in the range 3×10^{70} K/sec), the conclusions were that:

- (a) the hydrogen gas system, involving atomic hydrogen recombinations, should follow the equilibrium path,
- (b) the hydrogen-fluorine system should follow the equilibrium path,
- (c) the nitric oxide decomposition reaction should follow a frozen expansion path.

It is presumed that all the atomic recombination processes, such as



and

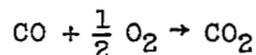


will be rapid, as is the hydrogen recombination, so that equilibrium with respect to these reactions would be expected.

Rate data for the recombination of hydroxyl radicals, OH, (refs. 19 and 20) indicate it might be expected to follow an equilibrium path.

Reaction rate data for the H_2 molecule are not known and, therefore, it is impossible to say whether this species would follow the equilibrium or frozen path upon expansion.

Application of some recent data on the rate of the reaction (ref. 21)



to the ramjet conditions of this report, where temperature change rates are on the order of 10^{60} K per second, indicate that the flow path would not be in equilibrium, but somewhere in between the frozen and equilibrium limits for this reaction. However, in the complex reaction scheme such as suggested by table II, there may be alternate, more rapid paths by which this same over-all resultant reaction could proceed.

No further remarks are made herein about the energy distributions within species for the pentaborane-air system for two reasons: (a) the nature of some of the species involved is currently being questioned, and (b) a large fraction of the energy of this system is involved in

phase changes of the boron oxide. Some discussion of the experimental behavior of pentaborane-air combustion products may be found in reference 22.

Residence Time

When reaction-rate information becomes available, it will require integration with the time history of the gas in the nozzle at various temperature and pressure levels. The residence time will depend primarily on the length of the nozzle. For a given nozzle, the residence time is little affected by whether the expansion is frozen or at equilibrium.

Two representative time-temperature curves are shown in figure 5. Both nozzles are 4 feet long to the throat, and 10 feet in over-all length. The only difference between the two nozzles is the contour of the convergent section. The nozzle-inlet temperature corresponds to that of a stoichiometric fuel-air mixture in a ramjet at Mach 7. A nozzle-inlet Mach number of 0.15 was assumed.

The general order of magnitude of residence times may be noted to be of the order of 2 to 3 milliseconds over most of the temperature change path. Changing the over-all length of the nozzle would, of course, change these times proportionately. Rates of temperature change for figure 5 are of the order of 2.5×10^{60} R per second over the major portion of the temperature change path.

The temperature level will, of course, be high in the convergent section. Since,

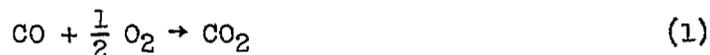
$$t \geq \left(\frac{2}{1 + \gamma_{\text{eff}}} \right) t_c \geq \text{approx. } 0.87 t_c$$

the temperature in the convergent section will be within approximately 87 percent of the combustion temperature. Similarly, the pressure level in the convergent section will be within approximately 50 percent of the combustion-chamber pressure p_c . Also, the residence time will be longest in the convergent section because of the subsonic velocities.

In general, the tendency toward equilibrium flow should be greater closer to the nozzle entrance, so that if the flow is examined at some point and found to approach equilibrium, equilibrium flow at any station upstream of that point is likely to occur. Conversely, if the flow approaches frozen-flow condition at some point, frozen flow at any station downstream is likely.

Estimated Minimum Performance

Since it appears that certain reactions may be expected to approach equilibrium flow in the nozzle, whereas for others it is uncertain, the conclusions of the preceding sections, with regard to reaction rates, provided the basis for the following reaction scheme. The following set of reactions was used for partitioning the dissociation energy (the numbers correspond to the reactions as given in table II):



Reactions (5), (6), (7), and (15) are "fast" reactions. Reaction (8) is a "slow" reaction. The rate of reaction (3) is unknown and the rate of reaction (1) was intermediate. (The designations of reactions as fast or slow are made with respect to the residence times indicated by fig. 5).

If reactions (5), (6), (7), and (15) are assumed to proceed rapidly enough to follow equilibrium flow in the nozzle, a probable minimum thrust level somewhat above the completely frozen expansion example may be estimated. Net jet thrusts calculated in this manner for the hydrocarbon and hydrogen cases are shown as a function of Mach number in figure 6 along with the complete equilibrium and completely frozen cases. The intermediate curves on these figures essentially assume that CO, NO, and the fraction of H₂ that does not take part in the OH reaction do not react, while the remaining species do. These intermediate curves might possibly be considered as the lower thrust limit curves based on present estimates of the reaction rates involved.

CONCLUDING REMARKS

As flight Mach number increases, and consequently combustion temperature levels increase, the fraction of the fuel energy that is used in dissociation of the normally complete oxidation products becomes increasingly great.

Net jet thrusts for frozen flow were only one-third to one-fifth of that for equilibrium flow at Mach 10 for the three fuels cited, a hydrocarbon, hydrogen, and pentaborane. This represents a large difference in fuel economy, and may well mean the difference between an operable and nonoperable system.

A complete theoretical analysis of the flow seems improbable at this time because of a lack of knowledge as to the exact reactions occurring and a lack of reaction-rate information for the reactions.

Examinations of the dissociated species involved and the energies associated with them, in the hydrocarbon and hydrogen mixtures, indicate that:

1. A major portion of the dissociation energy for the hydrocarbon mixture is involved in the CO molecule. Application of recent rate data indicates this species may not follow equilibrium flow.
2. In the hydrogen-air mixtures cited, the most of the dissociation energy is distributed in the chemical products H_2 , OH, H, and O. Atomic recombination reactions are probably fast and the flow, with respect to these H and O recombinations, will probably be in equilibrium.
3. Some reaction rate data on the OH radical indicate this species may follow an equilibrium path.
4. The reaction rates of H_2 are not known and equilibrium or frozen flow cannot be predicted from analysis cited herein.
5. Reactions involving NO decomposition are slow and undoubtedly follow a frozen path. In both the hydrocarbon and hydrogen cases cited, however, the amount of energy involved with this species is small.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 27, 1958

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TABLE I. - EQUILIBRIUM COMPOSITIONS OF STOICHIOMETRIC
HYDROCARBON-AIR MIXTURES

Constituent	Composition, mole fraction, at -		
	3.4 atm, 5430° R	1.0 atm, 4530° R	0.1 atm, 3250° R
CO	0.062	0.032	0.001
CO ₂	.06	.095	.130
O	.008	.002	
O ₂	.023	.014	.001
N ₂	.70	.72	.738
NO	.015	.006	
H ₂ O	.092	.116	.130
H ₂	.013	.0065	
H	.008	.002	
OH	.018	.0074	
Mol. wt.	27.4	28.1	28.8

TABLE II. - SOME REACTIONS AND THEIR ENERGIES
[Ref. 9.]

Reaction	Heat liberated at 298° K, kcal (reaction quantities in g moles)
(1) $\text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2$	67.61
(2) $\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$	9.45
(3) $\text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}$	57.80
(4) $\text{H}_2 + \text{O} \rightarrow \text{H}_2\text{O}$	116.90
(5) $2\text{H} + \text{M} \rightarrow \text{H}_2 + \text{M}$	103.80
(6) $2\text{N} + \text{M} \rightarrow \text{N}_2 + \text{M}$	185.1
(7) $2\text{O} + \text{M} \rightarrow \text{O}_2 + \text{M}$	118.2
(8) $\text{NO} \rightarrow \frac{1}{2} \text{N}_2 + \frac{1}{2} \text{O}_2$	21.6
(9) $\frac{1}{2} \text{H}_2 + \text{OH} \rightarrow \text{H}_2\text{O}$	68.10
(10) $\text{CO} + \text{O} \rightarrow \text{CO}_2$	126.71
(11) $\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H}$	26.01
(12) $\text{O} + \text{H} + \text{M} \rightarrow \text{OH} + \text{M}$	100.71
(13) $\text{H} + \text{OH} \rightarrow \text{H}_2\text{O}$	120.0
(14) $\text{OH} + \text{OH} \rightarrow \text{H}_2\text{O} + \text{O}$	19.3
(15) $\text{H}_2 + \text{OH} \rightarrow \text{H}_2\text{O} + \text{H}$	16.2
(16) $\text{NO} + \text{H}_2 \rightarrow \frac{1}{2} \text{N}_2 + \text{H}_2\text{O}$	21.6

TABLE III. - DISSOCIATED SPECIES AND THEIR ASSOCIATED ENERGIES

(a) Hydrocarbon plus air, stoichiometric; pressure, 3.4 atmospheres; temperature, 5430° R.

Constituent	Mole fraction	Kcal evolved in reaction	Percent of total reaction energy	Reactions assumed (see table II)
CO	0.062	4.19	59.2	1
^a H ₂	.013	.23	3.3	3,15
H	.008	.65	9.2	5,3
NO	.015	.32	4.5	8
O	.008	.47	6.6	7
OH	.018	<u>1.22</u>	<u>17.2</u>	15,7
		7.08	100.0	

(b) Hydrogen plus air, stoichiometric; pressure, 5.2 atmospheres; temperature, 5710° R.

^a H ₂	0.065	2.69	29.7	3,15
OH	.037	2.52	27.8	15,7
H	.032	2.59	28.6	5,3
O	.014	.83	9.2	7
NO	.015	.32	3.5	8
N	.0012	<u>.11</u>	<u>1.2</u>	6
		9.06	100.0	

(c) Pentaborane plus air, stoichiometric; pressure, 3.4 atmospheres; temperature, 5680° R.

O	0.014	0.83	5.9	7
H	.021	1.09	7.7	5,3
N	.0013	.12	0.9	6
BO	.086	9.28	65.9	(b)
^a H ₂	.026	.81	5.7	3,15
OH	.024	1.63	11.6	15,7
NO	.015	<u>.32</u>	<u>2.3</u>	8
		14.08	100.0	

^aPart of the hydrogen is used in the reaction with OH. The energy listed for H₂ is for the remaining H₂.

^bReaction: $BO + \frac{1}{4} O_2 \rightarrow \frac{1}{2} B_2O_3$; heat liberated at 298° K, 107.99 kcal/mole of BO.

4832

CO-3

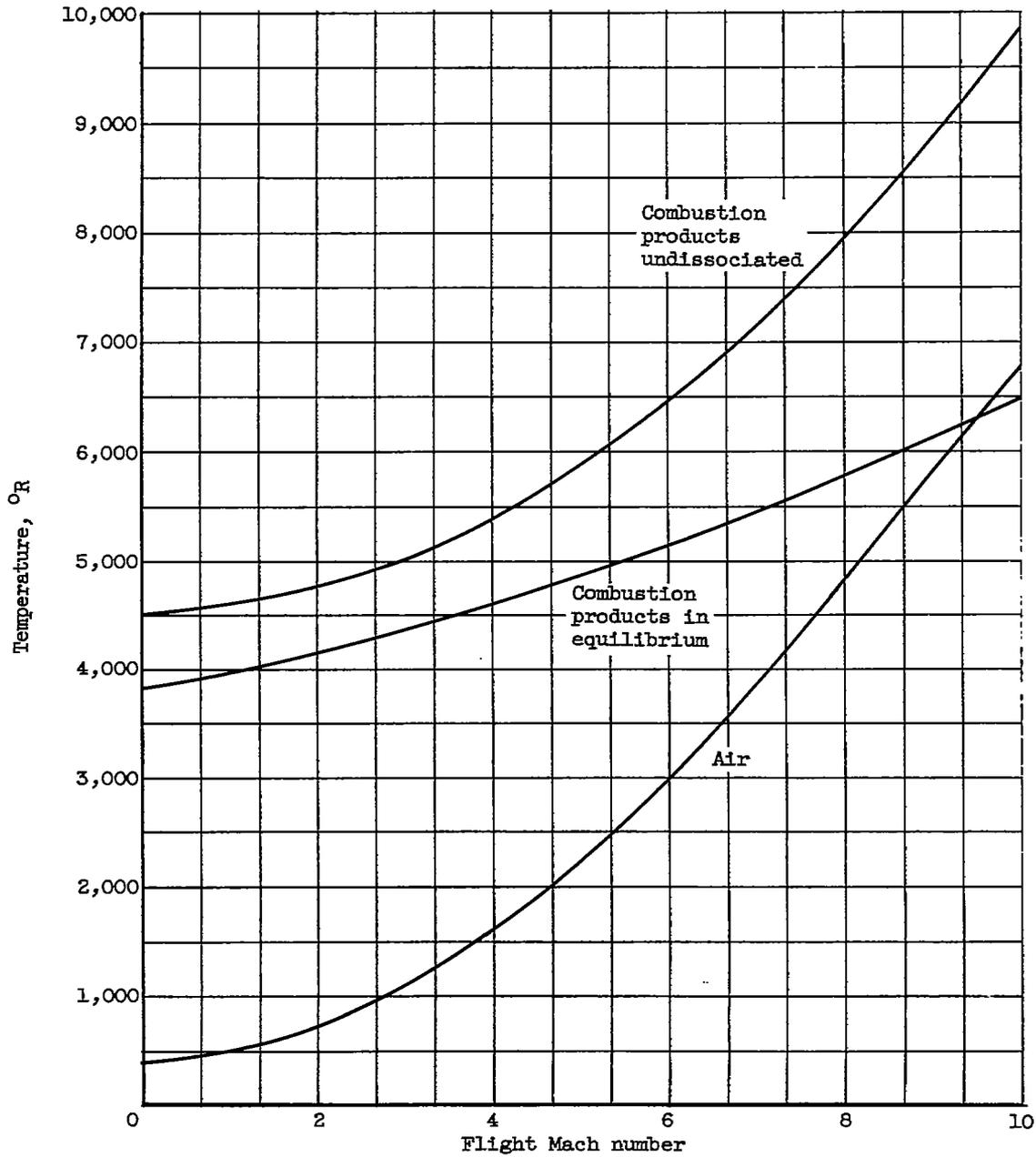


Figure 1. - Air and combustion product temperature variation with Mach number. Hydrocarbon fuel, $(CH_2)_n$ (stoichiometric).

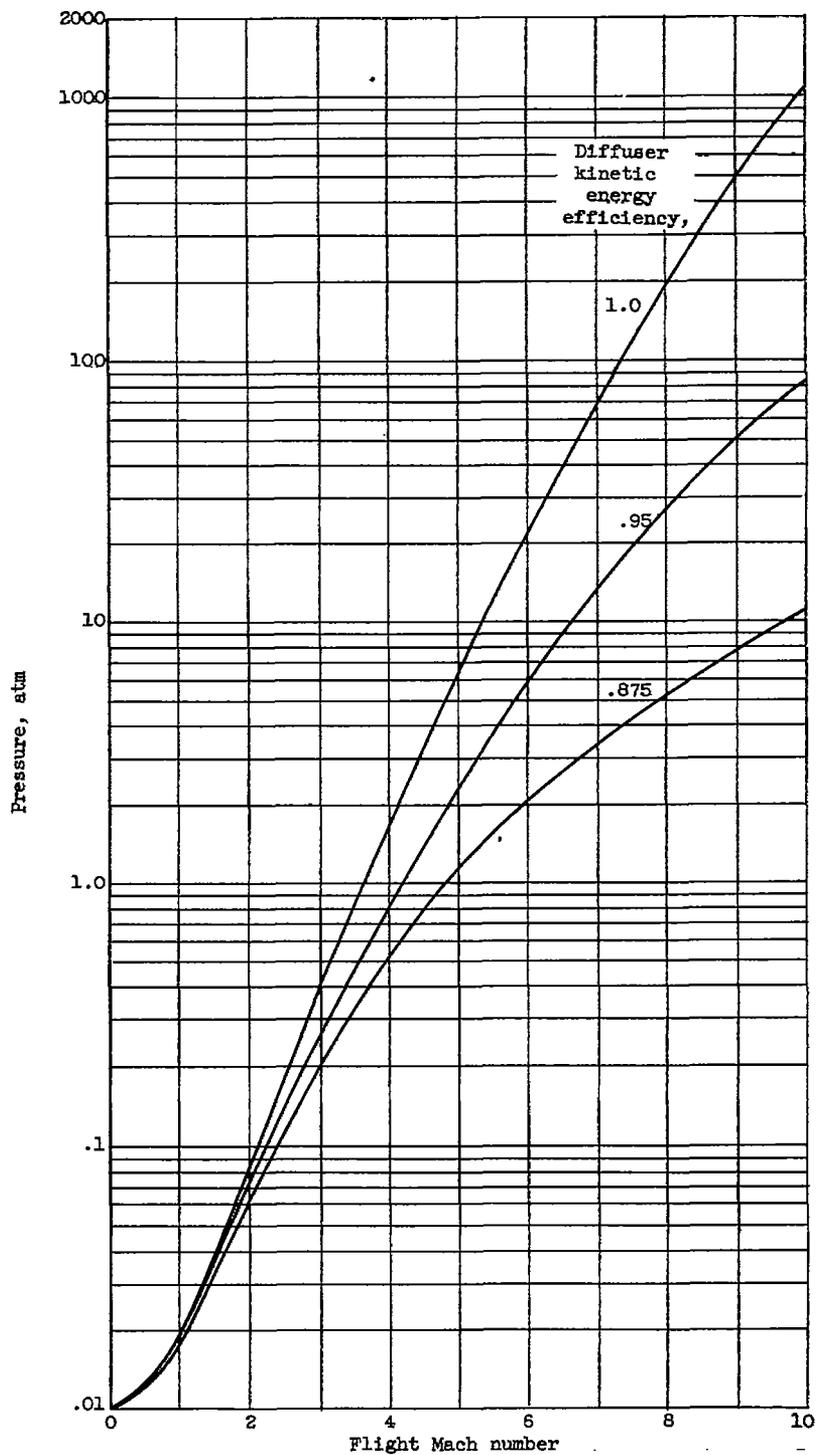
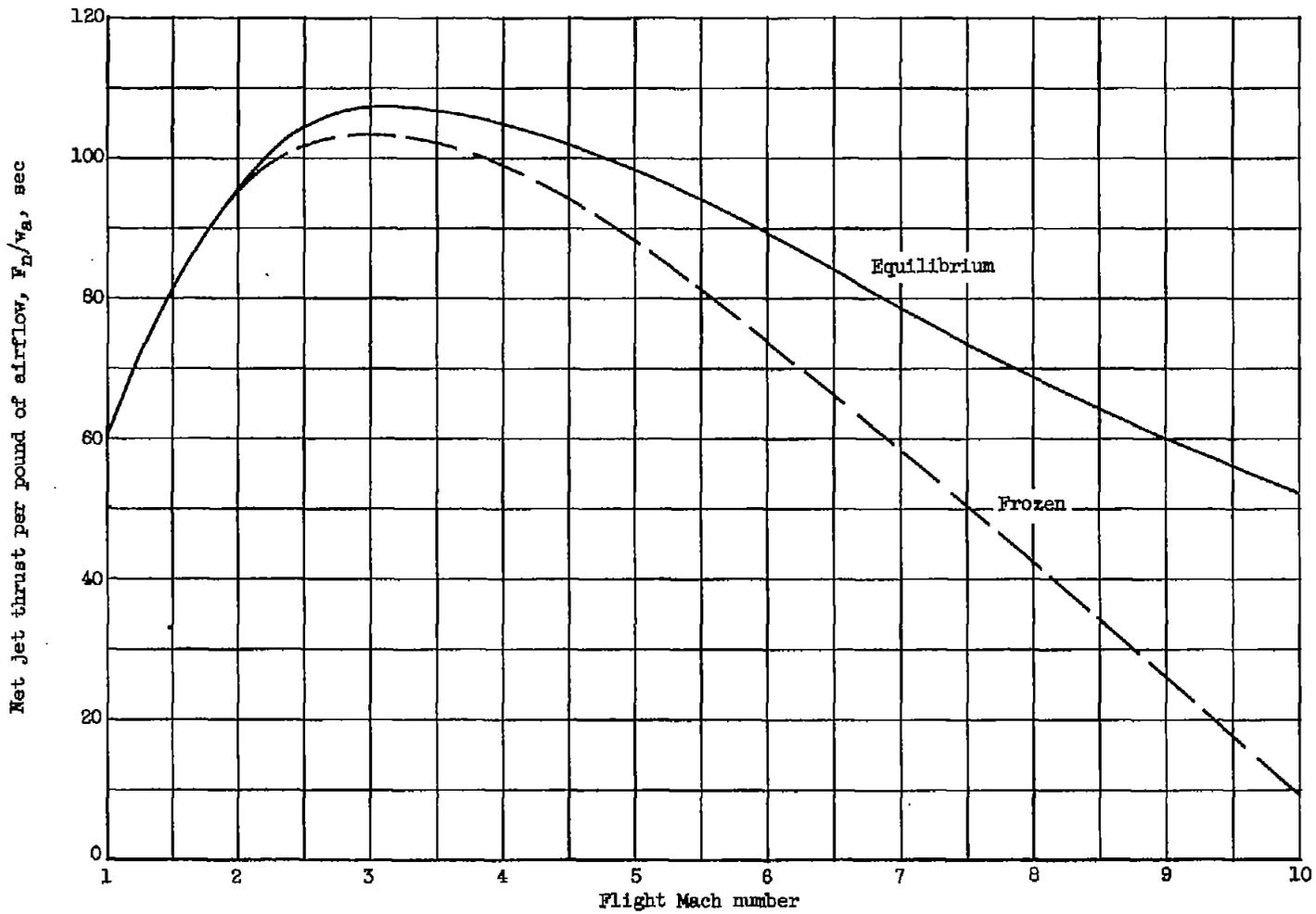
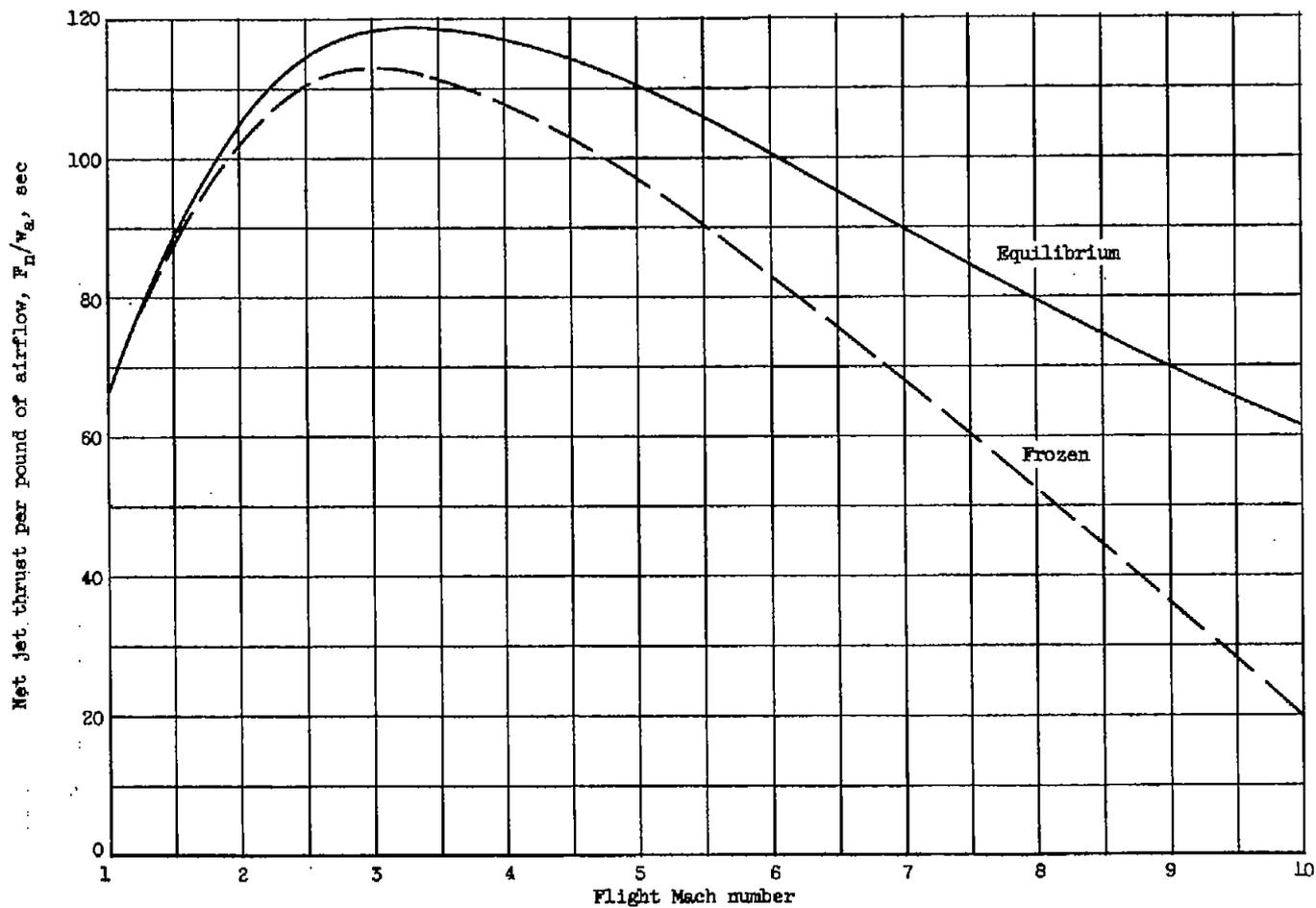


Figure 2. - Combustion-chamber pressure for various diffuser efficiencies. Altitude, 100,000 feet.



(a) Hydrocarbon plus air (stoichiometric).

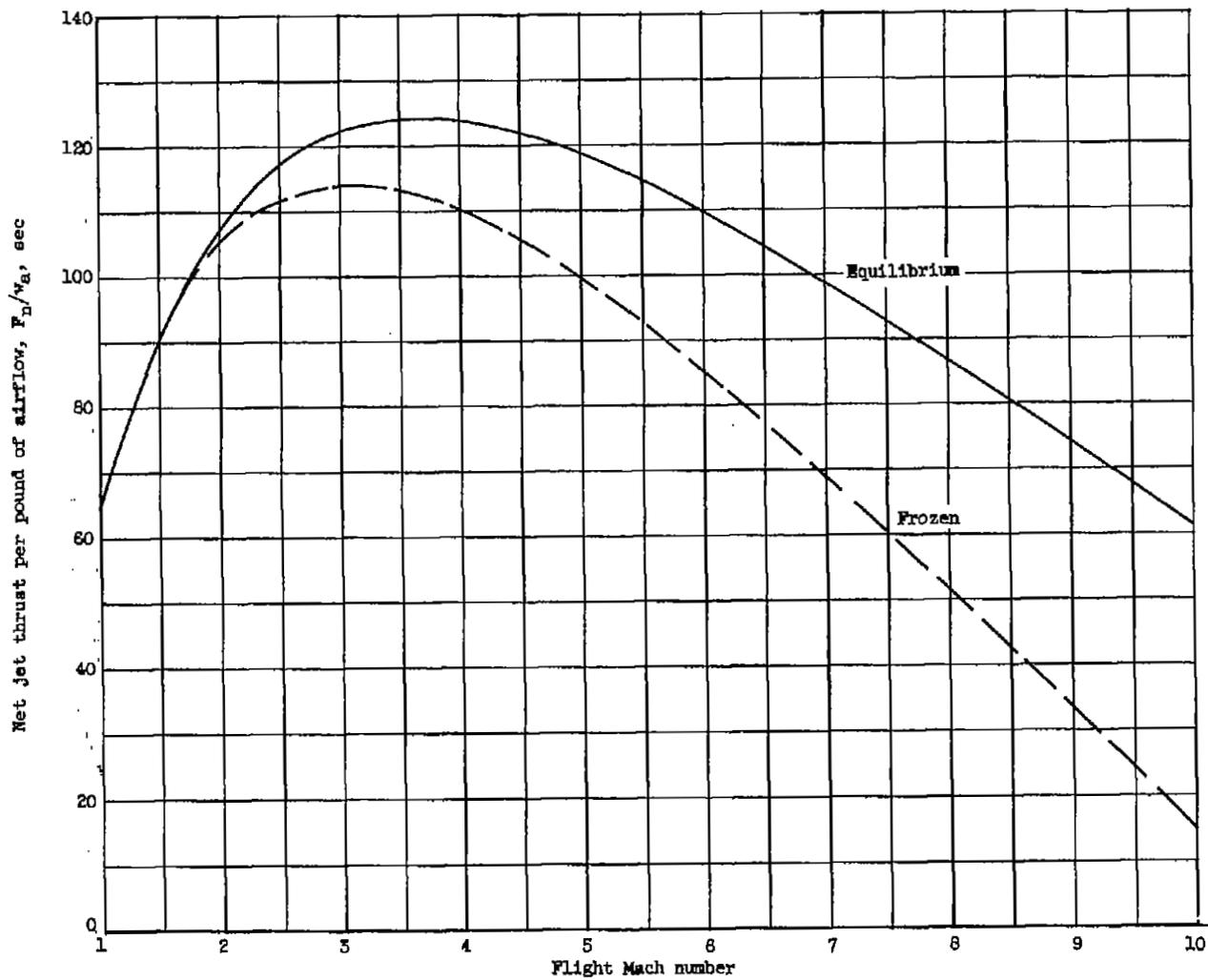
Figure 3. - Variation of net jet thrust with equilibrium and frozen flow for various Mach numbers. Altitude, 100,000 feet; diffuser kinetic energy efficiency, 0.875.



(b) Hydrogen plus air (stoichiometric).

Figure 3. - Continued. Variation of net jet thrust with equilibrium and frozen flow for various Mach numbers. Altitude, 100,000 feet; diffuser kinetic energy efficiency, 0.875.





(c) Pentaborane plus air (stoichiometric).

Figure 3. - Concluded. Variation of net jet thrust with equilibrium and frozen flow for various Mach numbers. Altitude, 100,000 feet; diffuser kinetic energy efficiency, 0.875.

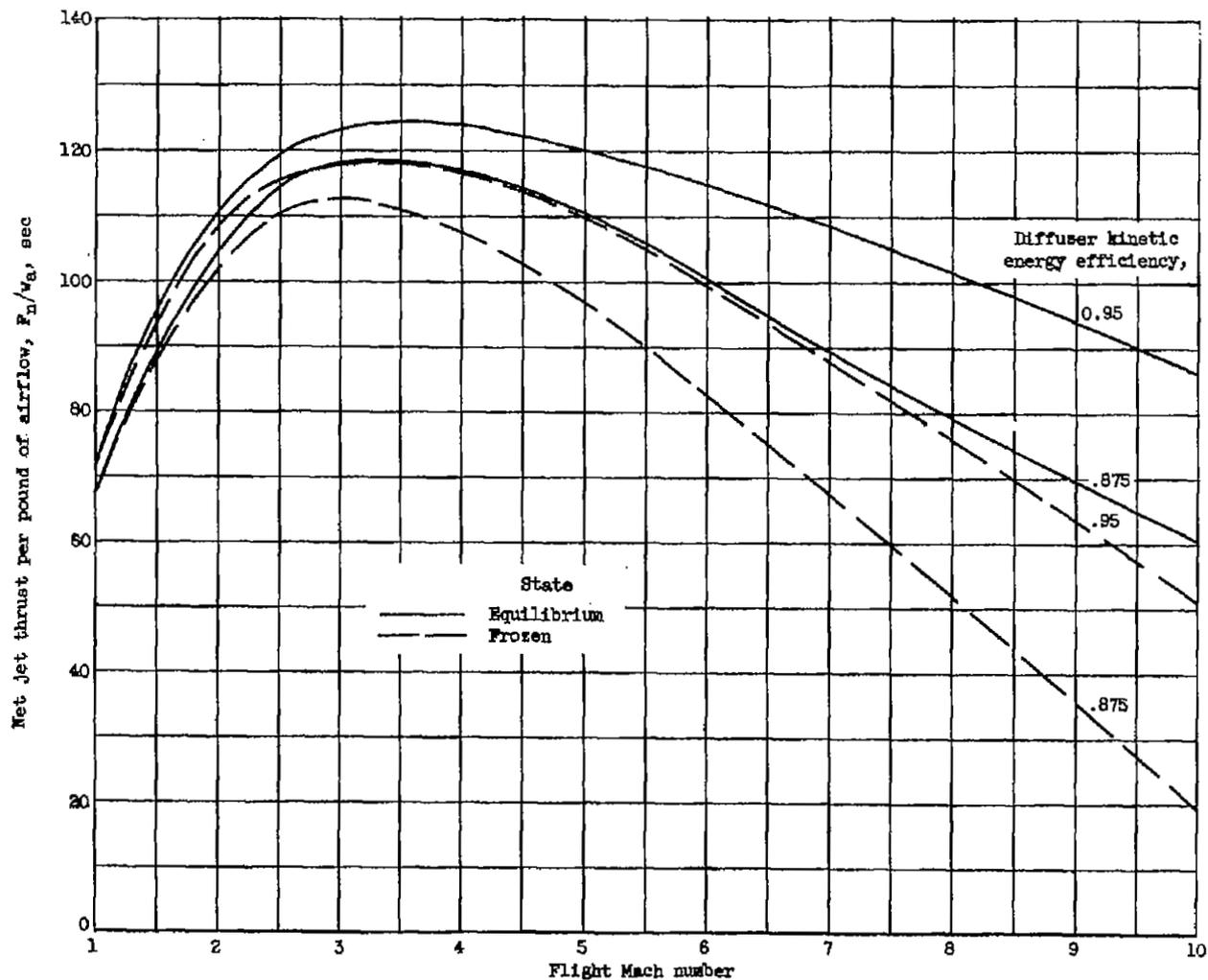


Figure 4. - Comparison of net jet thrust with equilibrium and frozen flow at diffuser kinetic energy efficiencies of 0.95 and 0.875 for various Mach numbers. Hydrogen plus air (stoichiometric); altitude, 100,000 feet.

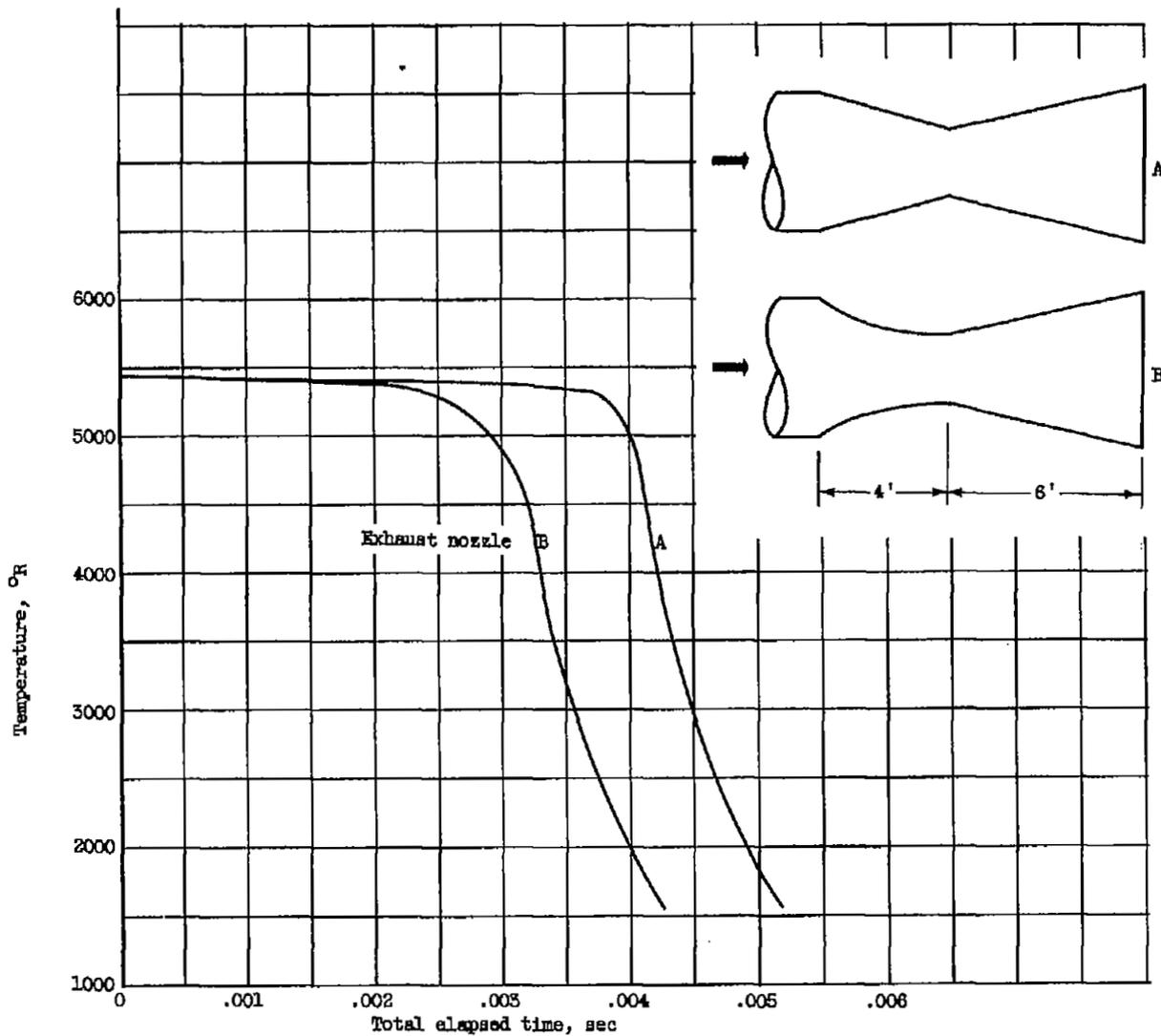
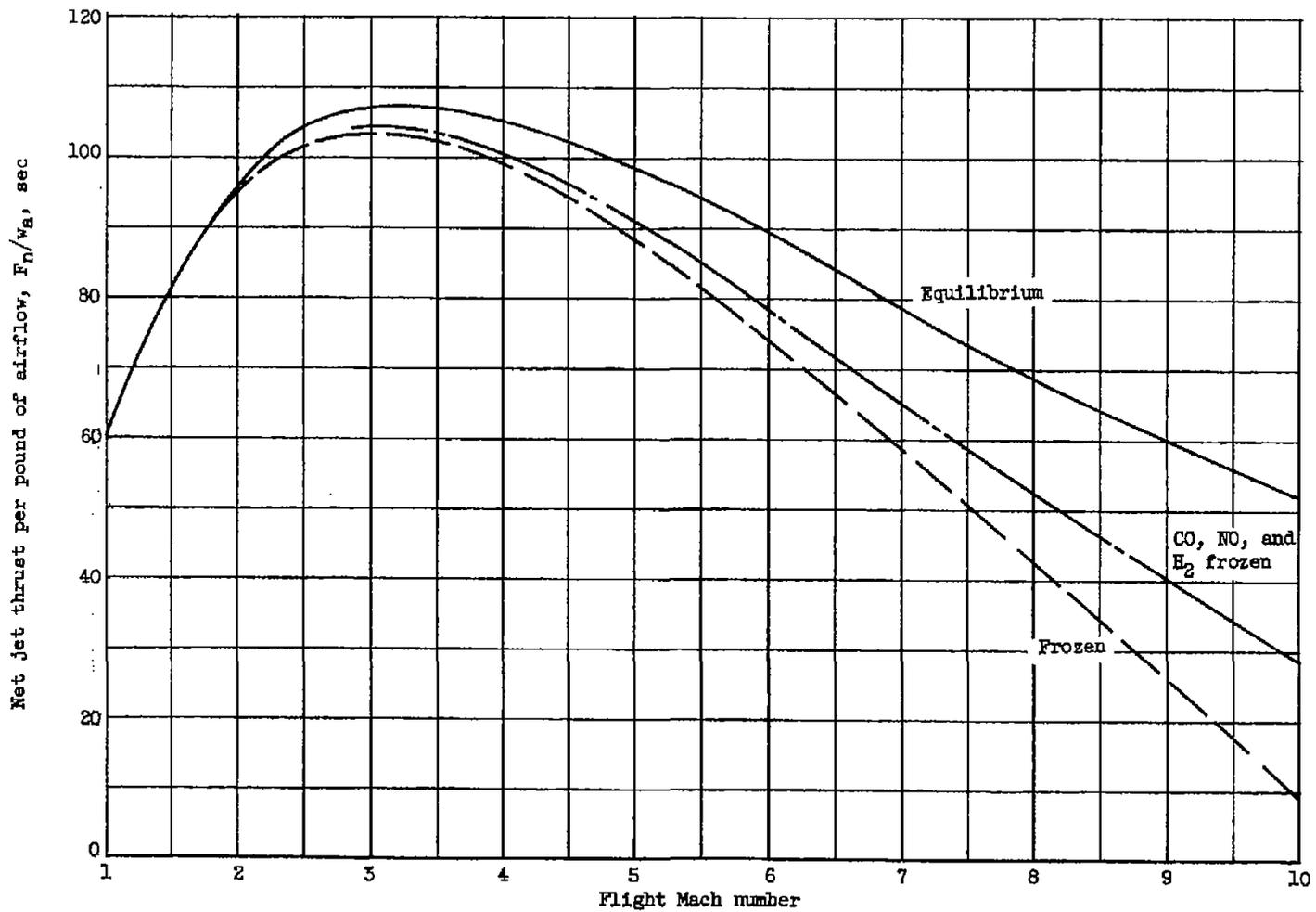
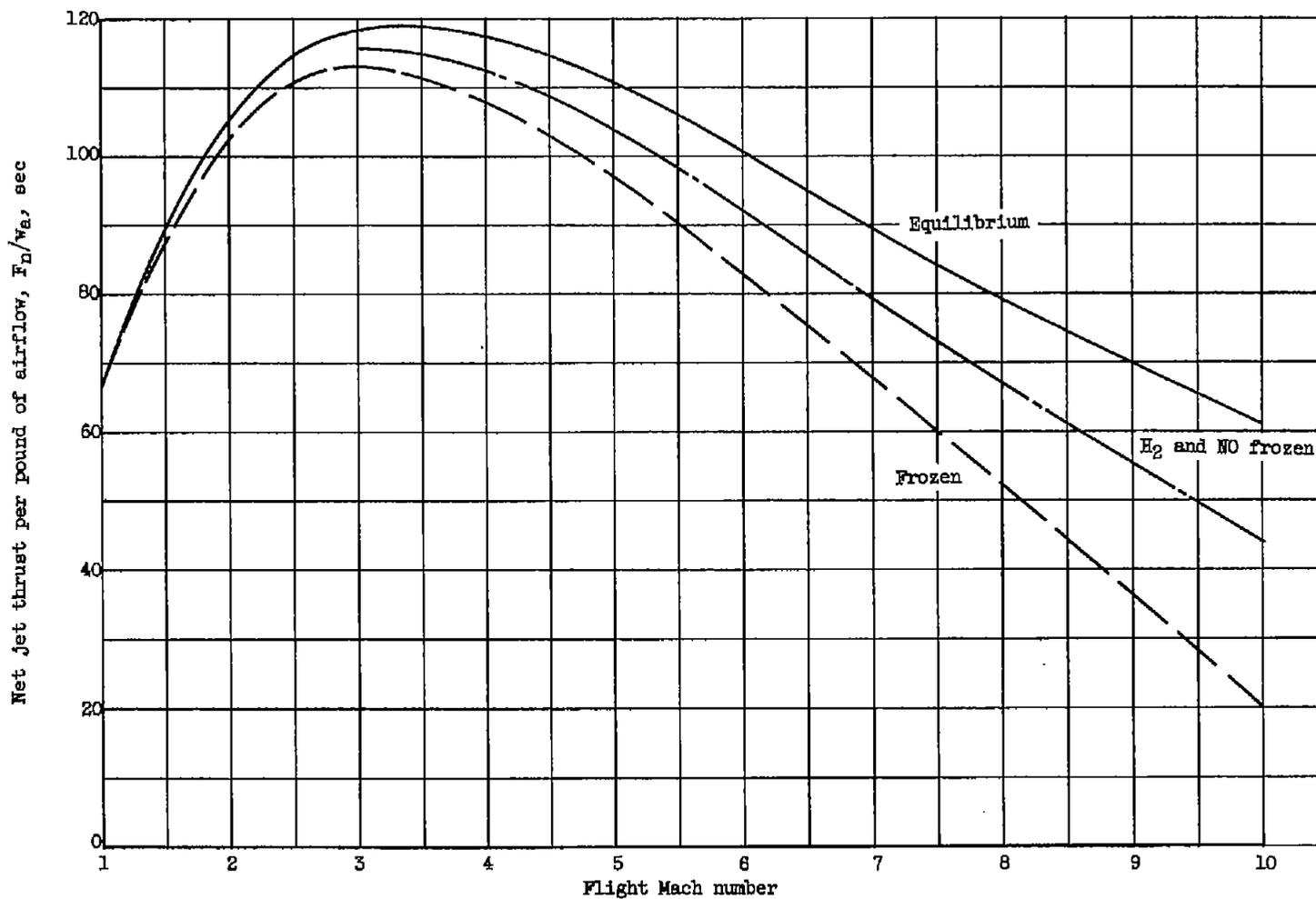


Figure 5. - Typical time-temperature variations in exhaust nozzle.



(a) Hydrocarbon plus air (stoichiometric).

Figure 8. - Comparison of estimated minimum net jet thrusts with net thrusts for equilibrium and frozen flow. Altitude, 100,000 feet; diffuser, kinetic energy efficiency, 0.875.



(b) Hydrogen plus air (stoichiometric).

Figure 6. - Concluded. Comparison of estimated minimum net jet thrusts with net thrusts for equilibrium and frozen flow. Altitude, 100,000 feet; diffuser kinetic energy efficiency, 0.875.

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